Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

NLR-TP-2000-265

High-acceleration performance of the Flat Swinging Heat Pipe

J. van Es and A.A. Woering

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2000-265

High-acceleration performance of the Flat Swinging Heat Pipe

J. van Es and A.A. Woering

This investigation has been carried out under a contract awarded by the Netherlands Agency for Aerospace Programmes, contract number 24932N.
The Netherlands Agency for Aerospace Programmes has granted NLR permission to publish this report.

This report is based on a presentation held on the International Conference on Environmental Systems, Toulouse, France, 10-13 July 2000.

Division: Space
Issued: 16 May 2000
Classification of title: Unclassified

Contents

(9 pages in total)

2000-ICES-175

High-acceleration performance of the Flat Swinging Heat Pipe

J. van Es and A.A. Woering
National Aerospace Laboratory NLR

ABSTRACT

The Flat Swinging Heat Pipe (FSHP) is a new cooling concept aiming at cooling of high power electronics at different acceleration loads, ranging from zero to ten times the earth's gravitation. The FSHP combines high heat transfer rates with the capability to withstand and operate under "any" acceleration condition.

This paper briefly outlines the basic working principle of the FSHP, and describes the experiments and tests at normal gravity both in a prototype high-g FSHP and in a glass experimental FSHP. The experiments focussed on fluid distribution, on measurement of liquid and vapour slug oscillations and on the assessment of the best working fluid and filling ratio. High-acceleration experiments were carried out on a rotating table, capable of generating 8.4 times the earth's gravitation at the FSHP center. The paper discusses aspects of fluid distribution, measurement of fluid oscillations, selection of the optimal working fluid and optimal filling ratio.

INTRODUCTION

The Flat Swinging Heat Pipe (FSHP) is based on the Pulsating Heat Pipe (PHP) and is developed by NLR for application under various gravitational loads. A promising application of the FSHP is as an alternative for the conductive heat exchangers in for example electronic boxes. It combines better heat transfer characteristics with high reliability, no maintenance and low costs.

LAYOUT

The FSHP (Figure 1) is a coldplate type of heat exchanger, an undulating pipe comparable with the PHP [1-6]. Whereas the PHP is made of small diameter pipe, the FSHP is a serpentine channel milled in a metal, aluminum plate. Because of constructional considerations and in view of the expected application milled grooves are preferred over piping. The grooved plate is covered by a thin top plate glued to the base plate, closing the FSHP channels.

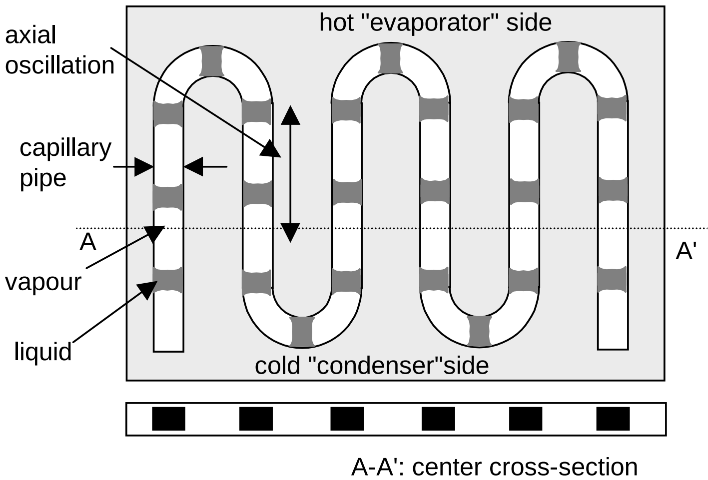


Figure 1 Flat Swinging Heat Pipe principle

In order to obtain a heat transport capability better than plain aluminum, the FSHP has to be partly filled with a working fluid, such as water or alcohol. Before filling, the FSHP is evacuated, and then the working fluid is injected, making the system operate under saturation conditions. As the amount of fluid determines the operational performance of the FSHP, appropriate care was taken during filling.

WORKING PRINCIPLE

The FSHP takes advantage of vapour slugs moving back and forth along the channel when heat is applied at arbitrary positions. This oscillatory motion is driven by the generation and the expansion of vapour bubbles at the heat sources, as described in for example [7,8]. The expansion causes the adjacent liquid slugs to accelerate. The resulting oscillatory motion dynamics is governed by inertia forced by sudden expansions due to heat input at the heat sources on the hot side of the FSHP in Figure 1.

Enhanced heat transport

Heat transport in the FSHP is a combination of the following mechanisms:

1. Evaporation at the heat sources, vapour transport by the oscillatory motion, condensation at the cold side. Heat transport is by means of the latent heat of the working fluid.
2. Radial diffusion in the Stokes layer. The oscillatory motion causes enhanced diffusion as described by Kurzweg et al. [9,10]. The heat transfer takes place from liquid core to the boundary layer and vice versa. This resembles high-frequency pulmonary respiration used in medicine.

REQUIREMENTS

The FSHP was designed for application in high-gravity environments. This poses stringent requirements on the FSHP structure, components and operation. The requirements influencing the operation and design of the FSHP are listed in Table 1.

Table 1 FSHP requirements

Temperature range	-40°C to 70°C
Acceleration range	1 to 10 g
Overall dimensions	150 x 100 x 2 mm
Average overall heat flux	1.0 W/cm^2

Envisaged application and location of the FSHP

The FSHP is designed to remove heat from printed circuit board electronics towards the sides of the electronic boxes where the heat is rejected to the environment or the main cooling system at any given acceleration value or direction. A concise description of the influence of different acceleration values and changes in geometry is given in [11].

EXPERIMENTS AT ONE G

The FSHP went through a range of experiments and tests in a steady (one g) experimental set-up, in order to obtain optimal dimensions, working fluid, production method and to gain insight in the working principle of the FSHP. For that purpose, two different types of FSHP's were made. A serpentine groove milled in an aluminum plate representing the design for use in high-g environments and a FSHP of glass piping for optical measurements and observation.

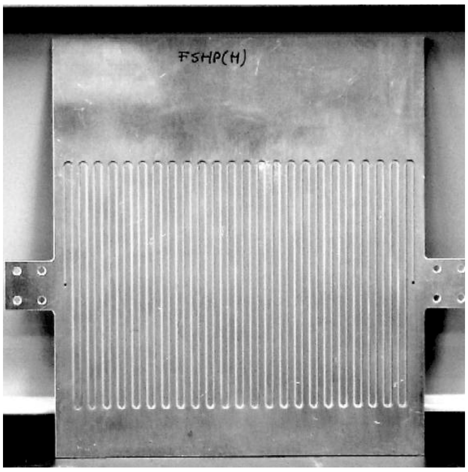


Figure 2 Milled FSHP

GROOVES MILLED IN AN ALUMINUM PLATE

The FSHP high-g prototypes (Figure 2) were subjected to a series of experiments to select the better working fluids, the optimal filling (in volume percentages) of the working fluid and to determine the enhanced heat transport capability.

A simple test set-up was constructed, see Figure 3, consisting of five electrical heater elements each dissipating a maximum of 20 W, a cold plate cooled by a fluid loop, some thermocouples and a CCD and IR camera.

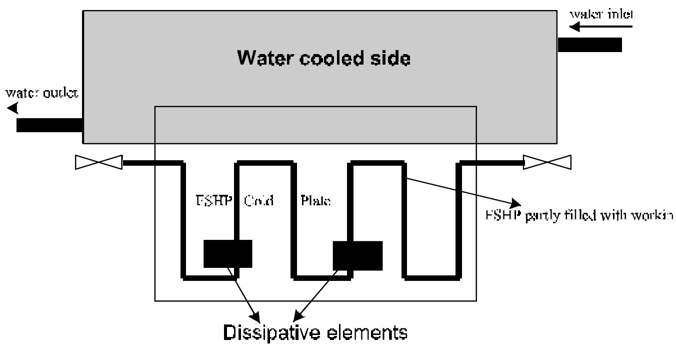
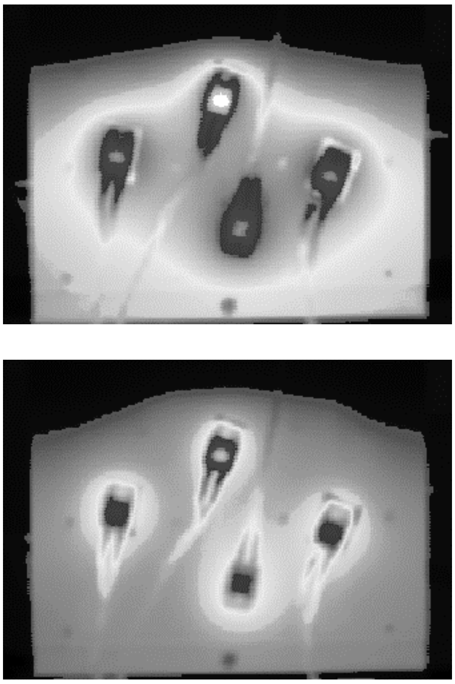


Figure 3 FSHP test set-up

EXPERIMENTS AND RESULTS

The difference between an operating and an empty FSHP is illustrated in Figure 4.



(a)

(b)

Figure 4 Infrared photograph of the first prototype FSHP, (a) FSHP not filled at 35 W, (b) FSHP filled with ethanol at 35 W.

Figure (a) shows an empty FSHP while in figure (b) the FSHP is filled with ethanol. The difference in spreading of the heat and the size of the hot spots is clear, indicating that application of a FSHP is worthwhile. Only the areas around the heaters are hot while the empty FSHP shows that a large region surrounding the heaters remains of high temperature.

<u>Selection of the filling ratio and the working fluid</u>

The filling is an important parameter for the FSHP performance. As an example, Figure 5 shows the performance of the FSHP (internal volume of approximately 4 ml) for different levels of filling at different temperature differences over the FSHP. Note that for each working fluid the graph differs. The comparison of the working fluids in Table 2 was made at a filling ratio of approximately 50% (2 ml) for both earth and high gravity.

Table 2 Comparison of some working fluids

Fluid	Distri-bution	1-g per-formance	high-g per-formance
acetone	good	good	good
fc-87	good	good	not available
ethanol	moderate	good	bad
water	bad	bad	not available

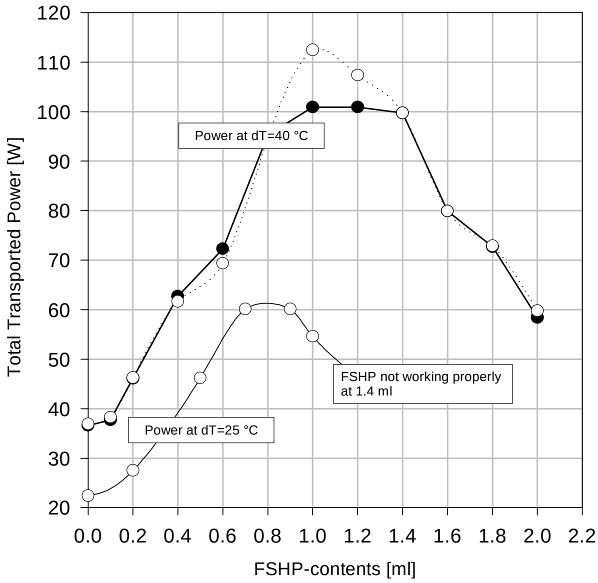


Figure 5 FSHP/ethanol performance vs. filling

<u>Enhanced heat transport</u>

A series of tests was carried out operating the FSHP in several different ways: 1) the ordinary set-up of applying heat one side and cooling on the other, 2) a cold plate on each side and applying heat in the middle, 3) using different distributions and numbers of hot spots with the previous two geometry options. These tests demonstrated that the performance of the FSHP is more or less constant showing an additional heat removal capacity (over a plain aluminium plate) of 60 to 120 %, the exact figure depending on the configuration. In the two-sided cooling layout, the additional effect is approximately 50 %.

GLASS PIPE SET-UP

The glass set-up is a FSHP of glass piping with an inner diameter of 1 mm. The glass FSHP is equipped with two valves for evacuating and filling purposes. The experiments in the glass FSHP aim at obtaining data on the fluid distribution, the fluid oscillation and dynamics.

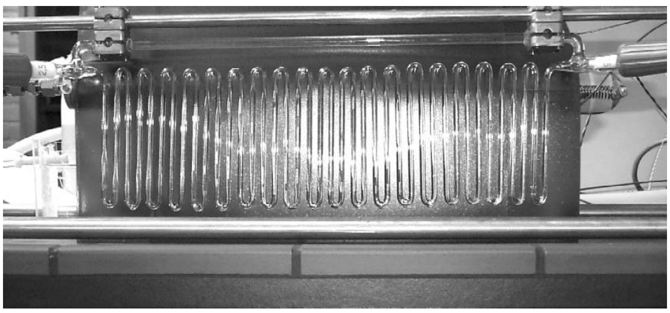


Figure 6 Glass FSHP

Fluid distribution

The fluid distribution at rest depends on the tube or channel dimensions, but especially on the working fluid properties. An important factor seems the saturation pressure inside a vapour slug, balancing the surface tension and wetting characteristics of the fluid. On the other hand, the way of filling, especially at high volume percentages, also severely influences the slug distribution.

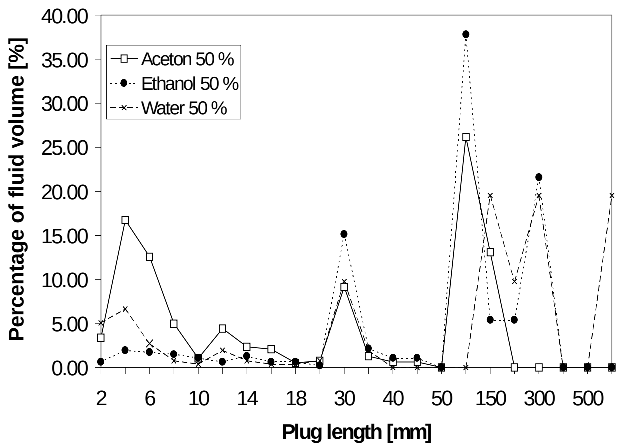


Figure 7 Fluid distribution

As an example, Figure 7 shows the results from optical measurement of liquid slug lengths. The distributions of three different working fluids are given for a liquid filling of 50 %. The graphs show that acetone distributes over a large number of small slugs and only some longer slugs, while water and ethanol generally form longer and less slugs. Although the number of slugs in itself does not determine the performance of the FSHP, it does influence the number of possible locations of evaporation. Thus, the number of slugs affects the on-set and continuation of evaporation, the FSHP engine. Furthermore, with an increasing number of vapour slugs the number of degrees of freedom increases. This may result in intensified "chaotic" behaviour.

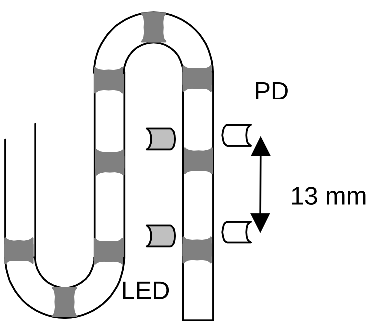


Figure 8 Slug sensor layout

Fluid oscillations

Besides the fluid distribution measurement an addition to the optical set-up is made in order to measure the vapour and liquid slug lengths, their numbers and their velocities. The slug sensor, see Figure 8, consists of two sets of a LED and a photodiode (PD), that can discriminate between a vapour or liquid slug by means of the difference in refractive index.

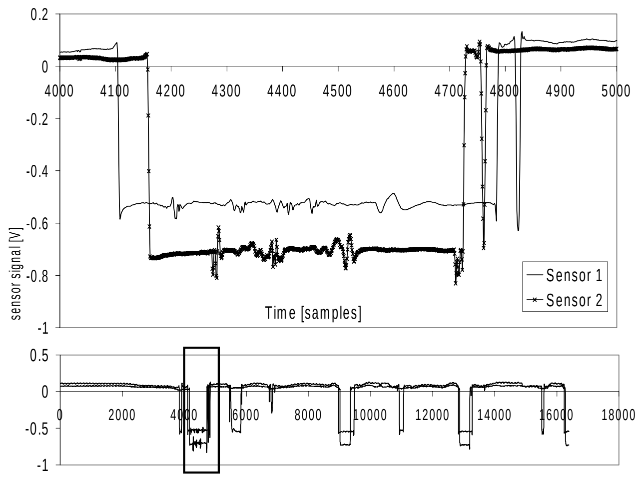


Figure 9 Fluid oscillation measurement, with acetone as working fluid at 50% filling

Results of a typical experiment using the slug sensor are given in Figure 9. The bottom graph shows a measurement of 1.6 seconds long with a sample rate of 10 kHz. A small piece of the bottom graph is enlarged in the top graph, showing a vapour slug passing the slug sensor. Although the signal is very clear, it is still rather difficult to extract useful data from the graph. For example the slug both enters and exits sensor 1 (Figure 9) first. This could mean that the slug collapses or that the oscillatory motion drives the slug back before it can fully pass sensor 2. In order to obtain more detailed information on this phenomenon, an adaptation of the current sensor is foreseen, such that more pairs of LED's and PD's are used and neighbouring pairs are closer together. Note that the small tail bubble does pass both sensors completely. Probably this is a bubble that broke loose from the large slug. This suggests that instead of collapsing, the slug started moving in the opposite direction before exiting the sensor at station 2. The velocity of the small bubble is approximately 2.1± 0.3 m/s and is representative for the liquid slug velocity in this particular experiment.

HIGH-ACCELERATION EXPERIMENTS

The high-acceleration experiments were carried to test and verify the proper operation of the FSHP under high-gravity conditions, for example experienced in fighter aircraft. Rather than improving the FSHP modeling, which was the goal of the aforementioned experiments. here compliance with the requirements of Table 1 was established.

EXPERIMENTAL SET-UP

The high-acceleration experiments were carried out in a set-up shown in Figure 10. The FSHP is mounted on a rotating table with a radial distance to the rotation axis of approximately 50 cm. A counterweight at the opposite side balances the rotating table when revolving.

The FSHP is heated by powering dissipating elements on the “hot side” of the FSHP. Cooling was achieved by mounting a Peltier element at the “cold side”. Thermo-couples were fixed on several locations on the FSHP, the Peltier element and on the base construction. The power lines and measurement lines were fed to the outside world through the rotating table axis.

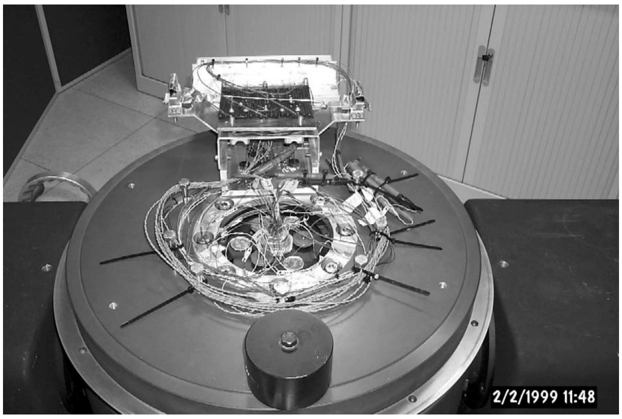


Figure 10 High-acceleration set-up

EXPERIMENTAL RESULTS

Several different experiments were performed with the experimental set-up previously described. In this section two experiments are discussed, one with the first stainless steel prototype using ethanol as working fluid and one with the second aluminum prototype with acetone as the working fluid. The character of the experiments was to operate the FSHP under ordinary operational conditions at rest and then increase the speed of the rotating table until the oscillating behavior of the FSHP breaks down.

The results of the high-acceleration testing of the first prototype of the FSHP are shown in Figure 11. The acceleration is increased stepwise until the enhanced heat transport ended. The graph shows an increase (first order response to a stepwise increase in acceleration) in temperature of the hot side of the FSHP after a few minutes spinning at 4.4g.

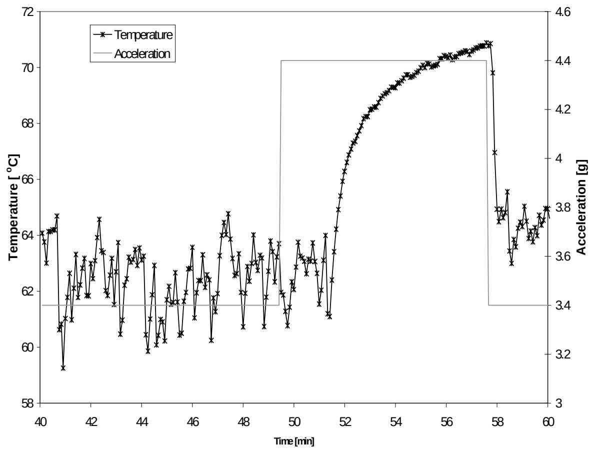


Figure 11 High-acceleration experiment with first stainless steel/ethanol prototype

A second prototype (aluminum/acetone) was subjected to a high-g test, see Figure 12, where the acceleration is increased in a number of steps up to 8.4g (the rotating table limit). The FSHP is thermally fully isolated from the outside world to avoid leaks. The temperature difference over the FSHP is approximately 22.5 °C and it remains constant with increasing acceleration. Up to 8.4 g, the FSHP shows stable operation and the acceleration requirement of Table 1 is approximately met.

FSHP VERSUS CONVENTIONAL COOLING

Apart from the heat transfer performance, the following parameters determine the feasibility of the FSHP as an alternative means of heat transport:

1. Volume
2. Mass
3. Power
4. High-acceleration performance
5. Reliability
6. Cost and production aspects

An electronics card of 150x100x1.78 mm is used as a model system at which the FSHP is applied. The aforementioned issues as well as the thermal performance were investigated.

As very small channel dimensions can be achieved by milling and no connections or couplings are used, the space required for using a FSHP is smaller than or equal to the space needed by any conventional liquid cooling method. Similar arguments are valid for the system mass, so the FSHP is not heavier than other liquid cooling. A major advantage of the FSHP is that in contrast with liquid, pumped cooling it does not require any additional power. Operation under high-acceleration is tested and the FSHP functions up to 8.4 g at least. The reliability of the FSHP can be secured because (1) there are no moving parts, (2) it is leak-tight as there are no seals or connectors and (3) start-up at any condition is possible.

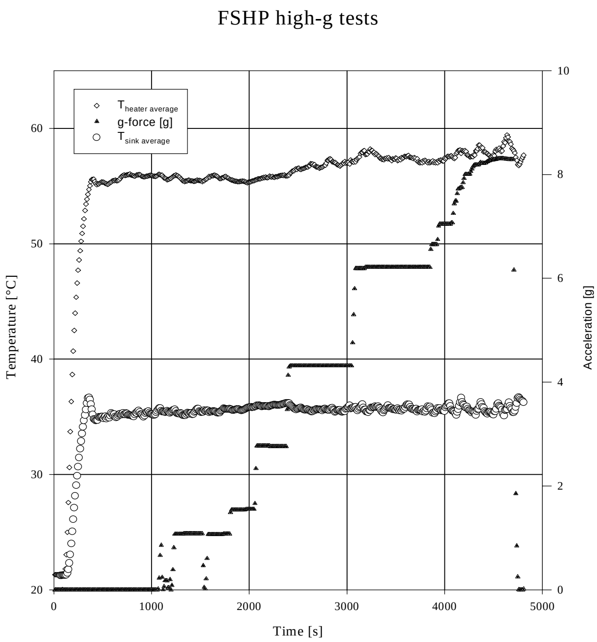


Figure 12 High-acceleration experiment with second prototype using acetone.

THERMAL PERFORMANCE

The thermal performance of different heat exchangers are calculated and compared with the FSHP. The maximum performance of a well conducting plate, with heat transfer to two cold walls is estimated to be 0.6 W/cm^2 (90 Watt/card) with a temperature difference of 35 °C. Theoretical values are also shown for a Beryllium Oxide plate (240 W/mK) and an Aluminium (180 W/mK) plate with one side cooled and a temperature rise of 40 °C. Experimental values of the conduction through an empty FSHP (of both prototypes) are measured and presented. The liquid cooled system is able to transport a maximum of 1.33 Watt/cm^2 (200 Watt/card, roughly estimated). For this system we assume a temperature difference of 40 °C as well.

The presented performances of the second (aluminium) FSHP-prototype are measured with the NLR test set-up using a water-cooled plate. This is schematically shown in Figure 3. Tests with acetone showed a heat flux of 0.67 W/cm^2 with a temperature rise of only 33 °C. The heat flux at a temperature rise of 40 °C is extrapolated from the heat transport capacities at lower temperature differences, resulting in a flux of 1.01 W/cm^2.

The results are summarised in Table 3. The table shows that liquid cooling has the best heat transport capability. The performance of the FSHP is 1.31 times better than the performance of the best conductive alternative at a temperature rise of 35 °C.

Table 3 Performance of the FSHP and alternative systems

System	Heat flux [W/cm^2]	ΔT [°C]
Liquid cooling	1.33 (estimated)	40
FSHP (NLR set-up)	1.05 (extrapolated)	40
FSHP (NLR set-up)	0.79 (extrapolated)	35
FSHP (NLR set-up)	0.67 (measured)	33
Conductive transport	0.60 (estimated)	35
Conductive transport (BeO)	0.34 (theoretical)	40
Conductive transport (empty FSHP)	0.26 (measured)	40
Conductive transport (Al 6061)	0.26 (theoretical)	40
Conductive transport (empty FSHP)	0.25 (measured)	40

CONCLUSIONS

The FSHP is a compatible, feasible alternative for conventional heat exchangers. It combines the advantages of two-phase cooling and the simplicity of a passive system.

The FSHP is more cost effective than the best conductive alternative (BeO), which is toxic, and therefore expensive in processing.

COMPARISON WITH CONDUCTIVE COOLING SYSTEMS

The FSHP-system is a suitable candidate for replacing the conductive heat exchanger when high performance is demanded. The advantages of the FSHP compared with alternative conducting cooling systems are:

- Smaller volume
- Better performance
- Equal or better performance with increasing temperature instead of the decreasing performance of conductive cooling systems with increasing

temperature (BeO, Aluminium) in the expected temperature range (-40 °C, 120 °C).

A possible point of concern compared to conductive cooling systems is:

- Risk of decreasing performance when the FSHP is leaking (e.g. perforated by a fragment)

COMPARISON WITH LIQUID PUMPED COOLING SYSTEMS

The FSHP-system is a possible alternative for liquid heat exchangers especially when space for quick disconnects and liquid lines is limited, when high reliability is required, and when cost effectiveness is a major issue.

The advantages of the FSHP over liquid cooling systems are:

- no quick disconnects
- no moving parts
- no additional power source needed
- cost effective
- smaller dimensions, especially the coldplate thickness

REFERENCES

1. Akachi, H, Motoya, S and Maezawa, S., Thermal performance of capillary tunnel type flat heat pipe, Proc. 9th Int. Heat Pipe Conf., Albuquerque, USA, 1995.
2. Wong, T.N. et al. Theoretical modelling of pulsating heat pipe, 11th Int. Heat Pipe Conf., Tokyo, Japan, 1999.
3. Akachi, H. and Polasek, F.' Pulsating heat pipes for space and avionic applications', CPL '96 Int. Workshop (ESA/ESTEC), The Netherlands, 1996.
4. Dobson, R.T. and Harms, H.M., Lumped parameter analysis of closed and open oscillatory heatpipes, 11th Int. Heat Pipe Conf., Tokyo, Japan, 1999.
5. Kiseev, V.M. and Zolkin, K.A. The influence of acceleration on the performance of oscillating heat pipe, 11th Int. Heat Pipe Conf., Tokyo, Japan, 1999.
6. Terpstra, M and Veen, J.G. van, Heat Pipes: Construction and Applications, EUR 10925 EN, Elsevier, London, 1987.
7. Yuan, H., Oguz, H.N. and Prosperetti, A., Growth and collapse of a vapor bubble in a small tube, Int. J. Heat and Mass Transfer, 42, 1999.
8. Yuan, H. and Prosperetti A. 'The pumping effect of growing and collapsing bubbles in a tube', accepted by J. Micromechanics and Microengineering, 1999.
9. Kurzweg,U.H and Zhao L, 'Heat transfer by high-frequency oscillations: A new hydrodynamic technique for achieving large effective thermal conductivities, Phys. Fluids, 27,1984
10. Kurzweg, U.H., Enhanced heat conduction in fluids subjected to sinusoidal oscillations, J.Heat Transfer, 107,1985.
11. Delil, A.A.M, Thermal-gravitational modelling and scaling of heat transport systems for applications in different gravity environments: super-gravity levels and oscillating heat transfer devices, accepted for presentation at the 30th Int. Conf. on Environmental Systems, Toulouse, France, 2000.

CONTACT

National Aerospace Laboratory NLR, Space Division, P.O. Box 153, 8300 AD Emmeloord, The Netherlands. E-mail: woering@nlr.nl, jvanes@nlr.nl.